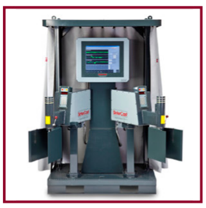
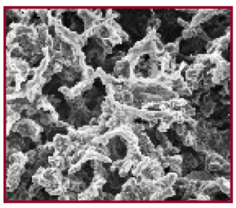
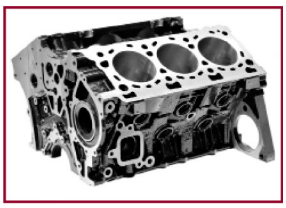
SinterCast
— Supermetal CGI —

The Effect of Metallurgical Variables on the Machinability of Compacted Graphite Iron







The Effect of Metallurgical Variables on the Machinability of Compacted Graphite Iron

S. Dawson and I. Hollinger
SinterCast Technologies AB, Sweden
M. Robbins and J. Daeth
Ford Motor Company Ltd., England
U. Reuter and H. Schulz
PTW, University of Darmstadt, Germany

Abstract

The influence of graphite shape, pearlite content and chemical composition have been investigated to determine their effect on the machinability of compacted graphite iron (CGI) . In the comparison to grey iron, the reduced sulphur content of CGI prevents the beneficial formation of a protective manganese sulfide layer on the cutting insert. This accounts for much of the difference in tool life during high speed continuous cutting. Beyond this critical mechanism, the machinability of CGI can be optimized by providing a consistent, low nodularity microstructure with a minimum of tramp elements such as titanium and chromium that form abrasive inclusions.

Introduction

Emissions legislation and the demand for higher performance from smaller engines have together driven the development of diesel engine technology over the past ten years. One of the most significant of these developments has been the advent of common rail and unit injector fuel management and delivery systems, which allow for higher cylinder pressures in direct injection diesel engines. While the higher peak firing pressures provide more efficient combustion, improved performance, reduced emissions and quieter engine operation, they simultaneously place increased mechanical loads on the main bearing region of the cylinder block, potentially resulting in premature fatigue failures. The irreversible trend toward higher peak firing pressures has prompted engine designers to seek stronger materials in order to meet their durability targets without increasing the size or weight of their engines. With at least 75% increase in tensile strength, 40% increase in elastic modulus and approximately double the fatigue strength of grey iron, CGI is ideally suited to meet the current and future requirements of diesel engine design. However, in order for CGI to gain widespread acceptance as a cylinder block material, its machinability should approach that of conventional grey cast iron.

In general, the three available avenues for optimizing the machinability of CGI include: improving the robustness of the insert materials; improving the machining techniques; and, improving the CGI itself. Although the present paper focuses on the extent to which variations in the CGI composition and microstructure can influence tool life, a brief review of recent developments in CGI machining techniques is also provided.

Background

Grey cast iron, compacted graphite iron and ductile iron are differentiated by the shape of the graphite particles. As shown in Figure 1, grey iron is characterized by randomly oriented graphite flakes while the graphite particles in ductile iron are present as individual spheres. In contrast, the graphite particles in CGI appear as individual 'worm-shaped' or vermicular particles. The particles are elongated and randomly oriented as in grey iron, however they are shorter and thicker, and have rounded edges. While the compacted graphite particles appear worm-shaped when viewed in two dimensions, deep-etched scanning electron micrographs (Figure 2) show that the individual 'worms' are connected to their nearest neighbors in a complex coral-like graphite morphology. Together with the rounded edges and irregular bumpy surfaces of the compacted graphite particles, the coral-like morphology results in strong adhesion between the graphite and the iron matrix. While the smooth-surfaced graphite flakes in grey iron promote crack initiation and growth and thus render the material relatively weak and brittle, the entangled compacted graphite morphology eliminates the natural cleavage paths thus providing strength and stiffness. The relative properties of the three cast irons are summarized in Table I.

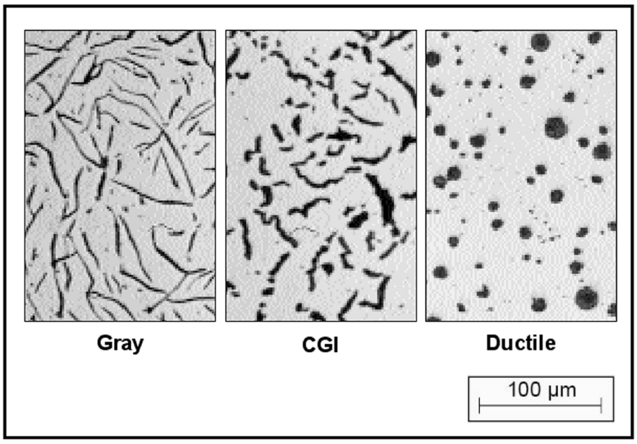


Figure 1: Grey iron, compacted graphite iron and ductile iron are differentiated by the shape of the graphite particles

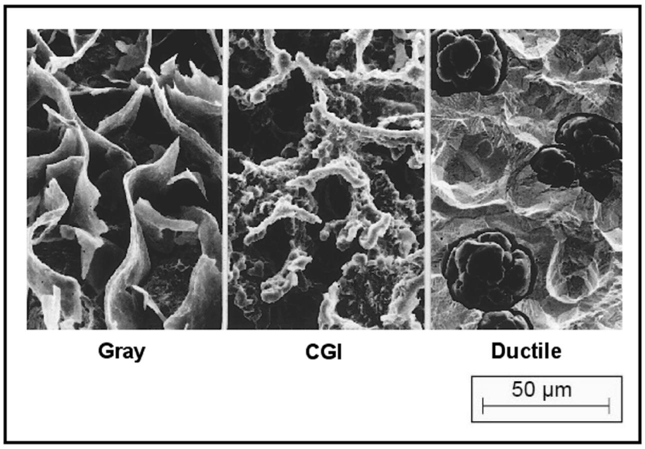


Figure 2: Deep-etched scanning electron micrographs show the three-dimensional shape of the graphite

Table I
Typical properties of pearlitic grey, compacted and ductile cast irons, after [1]

Property	Grey	CGI	Ductile
Tensile Strength (MPa)	250	450	750
Elastic Modulus (GPa)	105	145	160
Elongation (%)	0	1.5	5
Thermal Conductivity (W/mK)	48	37	28
Relative Damping Capacity	1	0.35	0.22
Hardness (BHN 10/3000)	179-202	217-241	217-255
R-B Fatigue (MPa)	110	200	250

In addition to the increased strength and stiffness of compacted graphite iron, conventional abrasion and scuffing tests show that CGI provides 30-50% better wear resistance than grey iron. While this is positive for cylinder block and liner applications, it further illustrates that CGI will be more difficult to machine than grey iron. As shown in Figure 3, low speed cutting (150-250 m/min) with conventional carbide inserts provides approximately 50% of the tool life of grey cast iron in both milling and turning operations. Similarly, milling at high speed (400- 800 m/min) with ceramic or polycrystalline cubic boron nitride (PCBN) also provides approximately 50% of the grey iron tool life. Under these conditions, the difference in the tool life of grey iron and CGI is generally commensurate with the increase in mechanical properties. However, the most significant difference in the machinability of CGI is in the high speed (>700 m/min) continuous cutting operations such as turning or cylinder boring. These speeds are particularly important as they represent cylinder boring cutting speeds in modern high speed, high volume transfer lines. Although a typical cylinder bore is only about 85 mm in diameter and 100 mm deep, the edge of the cutting insert remains in constant contact with the iron for approximately 100 meters as it spirals its way down the bore. Under these conditions, the ceramic and PCBN tool lives can be 10- 20 times lower than those obtained with grey iron. For this reason, the recent development work has focused on the critical high speed (high productivity) continuous cutting operations such as turning and cylinder boring.

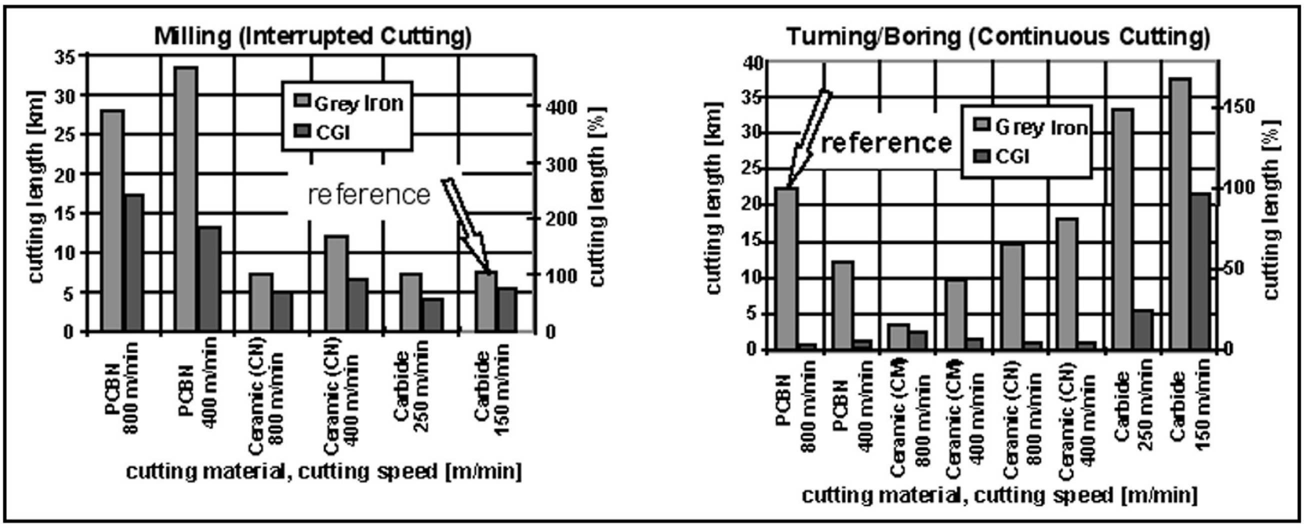


Figure 3: Comparative tool life for different tool materials in interrupted (milling) and continuous (turning/boring cutting of 70-80% pearlitic CGI and grey iron

In order to become a viable material for high volume cylinder block production, the industry would ideally like the machinability of CGI to approach that of current grey iron cylinder blocks under transfer line conditions. Specifically, CGI cylinder blocks should conform to a cycle time of less than 30 seconds with a cutting time of approximately 10-14 seconds per operation. The cutting inserts should also be durable enough to satisfy geometry and roughness specifications, for an entire 8-hour production shift.

In parallel to the extensive work being carried out by OEMs, tooling suppliers and research institutes on insert development and improved cutting techniques, the present study examined the extent to which the microstructure and metallurgy of CGI can contribute to improved tool life. In addition to the tool wear results, the potential for the various CGI modifications to be adopted into series production was evaluated against the following constraints:

- The metallurgical variations must not compromise the desirable properties of CGI.
- The metallurgical variations must not improve one machining operation at the expense of another.
- The modifications must be sufficiently minor to ensure that the product development work done thus far remains valid. Major modifications would require a new development cycle to validate material properties and engine performance.

The machinability of the various CGI alloys was evaluated in both milling and turning operations with a variety of cutting conditions and insert materials. However, because high speed cylinder boring is the most challenging operation, the emphasis of the current study was placed on continuous cutting, as simulated by turning operations on the external surface of representative test cylinders.

Experimental Procedure

The tool wear data presented in this paper were obtained by machining standard test pieces cast in a production foundry. The base iron was melted in 6 tonne coreless medium frequency induction furnaces and held in a 60 tonne coreless line frequency furnace as part of the standard base iron for ductile iron production. Base treatment was performed with a commercially available MgFeSi alloy followed by SinterCast thermal analysis and the addition of corrective amounts of 5 mm magnesium and/or 9 mm diameter inoculant cored wires to obtain the desired CGI microstructure. The milling and turning test pieces (Appendix A) were poured from a one-tonne production ladle. Specific details of test piece chemistry and microstructure are provided in each section of the paper as appropriate.

The milling test pieces were machined on a Deckel FP 4NC milling machine with a CeramTec MFS 08-06-75F4 cutter. The turning test pieces were machined on an Oerlikon-Boehringer VDF 180C lathe by outside turning with a single insert. All test pieces were pre-machined to remove the as-cast surface and establish a round and flat surface before collecting tool wear data. All cutting tests were conducted with commercially available insert grades and geometries. The cutting conditions for the PCBN and carbide milling and turning tests are summarized in Table II, while the geometrical data for the turning and milling tools are provided in Table III. The specific details of other cutting tests are summarized in each section as appropriate. The end-of-life criteria for all test conditions presented in Table II was defined as either 300µm flank wear or an R_z surface roughness of 25 µm.

Table II
Standard Machining parameters for the PCBN and carbide milling and turning tests

Insert Material	Supplier Name	Insert Grade	Geometry Designation	Speed (m/min)	Feed Rate	Depth (mm)
Milling Test					(mm/tooth)	
Carbide	Kennametal	CH 2	SNMA 1204ENEN	150	0.15	2.0
Carbide	Kennametal	CH 2	SNMA 1204ENEN	250	0.15	2.0
PCBN	Sumitomo	BN 600	SNGN 120408	400	0.15	2.0
PCBN	Sumitomo	BN 600	SNGN 120408	800	0.15	2.0
Turning Tests					(mm/rev)	
Carbide	Kennametal	KC 9120	SNMA 120408	150	0.3	0.20
Carbide	Kennametal	KC 9120	SNMA 120408	250	0.3	0.20
PCBN	Sumitomo	BNX 10	SNGN 120408	400	0.3	0.15
PCBN	Sumitomo	BNX 10	SNGN 120408	800	0.3	0.15

Table III
Geometry for the milling and turning tools

Milling Tool		Turning Tool	
Tool specification	CSRNL2525M12-IC7	Diameter (d)	80m
Lead Angle (χ_r)	75°C	No. of Teeth	6
Rake Angle (γ)	-6°C	Radial rake (γ_f)	-8°30'
Angle of inclination (λ_s)	-4°C	Axial Rake (γ_p)	-7°C
Included Angle (δ)	90°C	Lead Angle (χ_r)	75°C

The Effect of Graphite Shape

According to the ASTM A842-85 specification for compacted graphite iron, CGI should contain more than 80% of the graphite particles in the compacted or 'wormlike' form and fewer than 20% of the graphite particles in spheroidal form. Flake-type graphite causes local weakness and is inadmissible.

As the properties of cast irons are primarily determined by the shape, size and quantity of graphite particles, a series of tests were conducted to determine the effect of graphite shape on machinability. The tests were limited to the high speed turning operation using PCBN at 800 m/min, according to the cutting conditions presented in Table II. The microstructure and composition of the materials tested are summarized in Table IV.

Table IV
Microstructure and chemistry details for the 800 m/min PCBN turning tests as a function of graphite shape

Material Name	Graphite Shape (%)			Pearlite (%)	BHN	Chemistry (%)							
	Flake	CGI	Nodules			C	Si	Mg	Cu	Sn	Mn	S	Cr
Grey	100	0	0	100	193	3.18	2.18	--	0.19	0.006	0.74	0.086	0.14
Flake + CGI	40-60	40-60	<5	>90	207	--	--	--	--	--	--	--	--
CGI	0	>95	<5	70-80	220	3.73	2.25	0.011	0.47	0.033	0.41	0.015	0.03
50-Nod	0	45-55	45-55	>90	235	3.74	2.35	0.026	0.90	0.026	0.41	0.012	0.03
85-Nod	0	<20	>80	>90	245	3.68	2.20	0.040	0.94	0.10	0.40	0.010	0.03

As shown in Figure 4, the PCBN tool life continually decreases as the graphite shape changes from a fully flake structure in conventional grey iron to a 50/50 flake/compacted structure and on toward conventional ductile iron (85%) nodularity. As previously indicated in Figure 3, the CGI-alloy has only about 10% of the tool life obtained in conventional grey iron. The most significant decrease in tool life occurs as the iron changes from a conventional pearlitic grey iron to a mixed flake/compacted structure. Thereafter, the decrease in tool life is less pronounced. While the scaling of Figure 4 may initially suggest that there is no significant difference between CGI and higher nodularity microstructures, the tool life for the 5% nodularity CGI alloy is 40% higher than for the 50% nodularity alloy and 3.5 times longer than for the 85% nodularity alloy. As CGI is obviously more difficult to machine than grey iron, every effort to reduce nodularity will also contribute to the CGI tool life. This result reinforces the ASTM A 842-85 specification for CGI to limit the nodularity in the 0-20% range for extensively machined components.

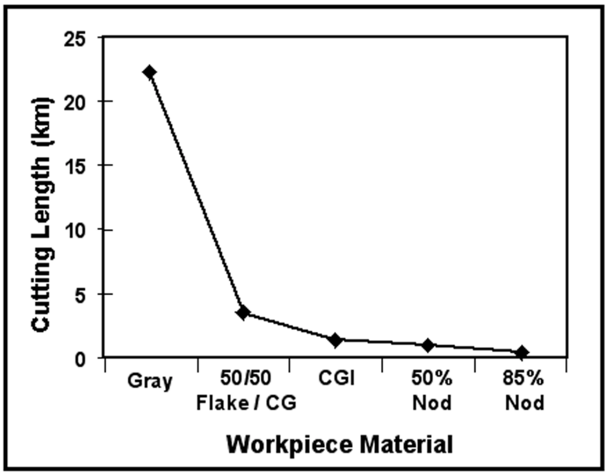


Figure 4: The influence of graphite shape on tool life for PCBN turning at 800 m/min

The dramatic decrease in tool life as the graphite structure changes from flake to a 50/50 flake/compacted structure indicates that changes in graphite shape alone cannot account for the high speed machinability of CGI relative to grey iron. Intuitively, the 50/50 structure should have provided an intermediate result, however, the tool life was more similar to the CGI than to the grey iron, despite that the tensile strength of the 50/50 flake/CG material (325 MPa) was more similar to that of the conventional grey iron (260 MPa) than to the CGI (435 MPa).

The surprising result of the flake patch trials indicates that other factors must be active in determining the machinability of CGI. The most significant of these was the fact that the 50/50 flake/compacted alloy was produced from a standard desulphurized and Mg-treated iron used for the production of CGI and ductile iron. Although the mechanical properties of the 50/50 flake/compacted alloy are more similar to grey iron, its production technique and melt history are more similar to the CGI alloy. The potential influence of the base iron composition was therefore investigated and will be reported upon later in this paper.

Alloyed Grey Iron

Some car and truck manufacturers are currently investigating alloyed grey iron as an alternative means of providing higher strength materials for their cylinder block applications. The addition of alloying elements such as chrome, tin, manganese, boron, copper, titanium, molybdenum and nitrogen, among others, provides solid solution hardening of the ferrite phase thus increasing the hardness and tensile strength. Generally, the alloying additions provide a 20-25% increase in hardness and tensile strength (from approximately 250- 300 MPa) but only a 5-10% increase in elastic modulus and fatigue strength. In parallel to the evaluation of graphite shape, a controlled test was conducted to evaluate the effect of alloying additions on the machinability of grey cast irons. In this case, a proprietary alloyed grey iron for passenger car diesel applications was compared to the materials previously presented in Figure 4. The direct comparison to the conventional grey iron isolates the influence of the alloying additions (approximately 0.3% Cr and 0.25% Mo) in the presence of a consistent flake graphite microstructure with 100% pearlite. The tests were conducted for PCBN and carbide turning under the conditions presented in Table II.

As shown in Figure 5, the tool lives achieved with the alloyed grey iron, for both PCBN and carbide turning, are more similar to the 70-80% pearlitic CGI results than to the conventional grey iron results. This result again demonstrates that graphite shape is not the only active factor in determining the machinability of cast irons. The addition of hardening alloys has a significantly negative influence on tool life. Although the alloyed grey iron only provides 20-25% increase in tensile strength and 5-10% increase in fatigue strength, it does not provide appreciably better tool life than conventional compacted graphite iron. It is thus evident that the CGI provides significantly higher strength benefits than the alloyed grey iron with only a small incremental loss of machinability.

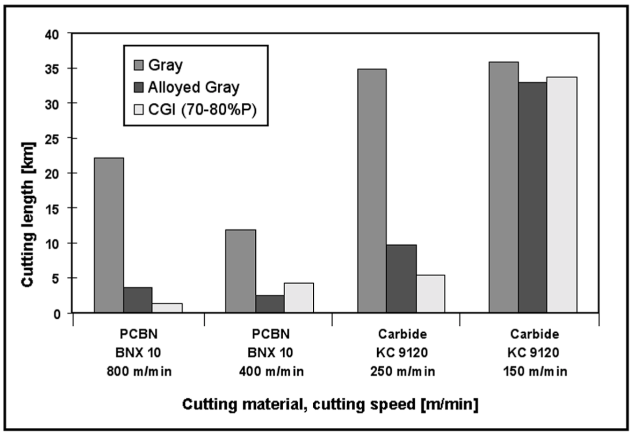


Figure 5: Tool life for conventional grey iron, alloyed grey iron, and 70-80% pearlitic CGI for PCBN and carbide turning

The Effect of Pearlite Content

Cast irons are a composite material comprised of graphite particles in an iron matrix. The properties of the cast iron are ultimately determined by both the shape of the graphite particles and the form of the iron matrix: either ferrite or pearlite. For a typical compacted graphite iron, with less than 10% nodularity, the effect of increasing pearlite content on tensile strength, hardness and elongation are shown in Figure 6. While increasing pearlite content increases the tensile strength and hardness of CGI, it is intuitive that it will also influence tool life.

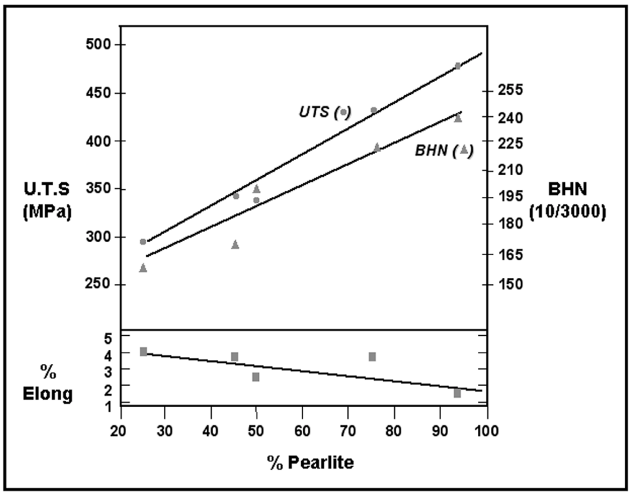


Figure 6: The effect of pearlite content on the ultimate tensile strength, hardness and elongation of 0-10% nodularity CGI in as-cast 25mm diameter test bars After [1]

During solidification in the temperature range of approximately 1175-1120°C the iron matrix initially forms as austenite, the non-magnetic body-centered-cubic form of iron found in stainless steels. As the iron cools below approximately 725°C the austenite transforms into either ferrite or pearlite. If the cooling rate through 725°C is slow enough, and the chemical conditions are favorable, the carbon atoms present in the austenite will diffuse to the graphite particles resulting in a ferritic matrix. However, if the carbon atoms cannot escape from the iron matrix, pearlite will form. Pearlite is simply a carbonsaturated form of ferrite where the excess carbon forms as Fe_3C (iron carbide or cementite) plates within the ferrite. These hard Fe_3C plates reinforce the iron matrix to make it harder and stronger, and more difficult to machine.

When viewed with a conventional microscope, a typical etched cast iron sample may show ferritic grains, pearlitic grains and graphite particles. As shown in Figure 7(a), the light colored ferritic grains (A) are easily distinguished from the dark colored pearlitic grains (B) and the graphite particles (C). The free ferrite preferentially forms adjacent to the graphite particles as this is where the carbon atoms are best able to diffuse out of the iron (either liquid or solid) and deposit onto the graphite. At higher magnification, Figure 7(b), it can be seen that the dark pearlite grains are actually a fingerprint type of structure with ferrite bands (D) sandwiched between the thin Fe_3C plates (E). Ferrite can thus be present in the form of free ferrite grains (A) or contained ferrite bands (D).

In order to fully evaluate the effect of pearlite on machinability, both the microscopic effect: the amount of Fe_3C in the pearlite grains; and, the macroscopic effect: the proportion of pearlitic vs ferritic grains, should be considered. In a previous study, Bates [2] has shown that the Fe_3C content in the pearlite phase of production iron castings can vary from approximately 8-15% depending on product chemistry and shake-out/cooling conditions. Further, the study showed that higher Fe_3C contents result in significantly reduced tool lives during the drilling of grey cast iron. Because shake-out practices predominate in defining the cooling rate of production castings, it is very difficult to change and control the Fe_3C content of the pearlite phase on a given moulding line. While the Fe_3C content of the pearlite phase cannot account for the significant differences between the high speed boring of grey iron and CGI, it may be an important parameter in accounting for differences between the machinability of castings from different foundry sources.

Dating to 1994, the discussions over the optimal pearlite content for CGI cylinder blocks were based on hardness. At equal pearlite content, CGI is approximately 10-15% harder (Brinell) than grey cast iron. Therefore, to maintain continuity with the known grey iron specifications, two basic CGI cylinder block materials were proposed as follows:

- 100% pearlitic CGI, which ensured that CGI had the same pearlite content as the current grey iron standard.
- 70-80% pearlitic CGI, which ensured that CGI had the same hardness level as the current grey iron standard.

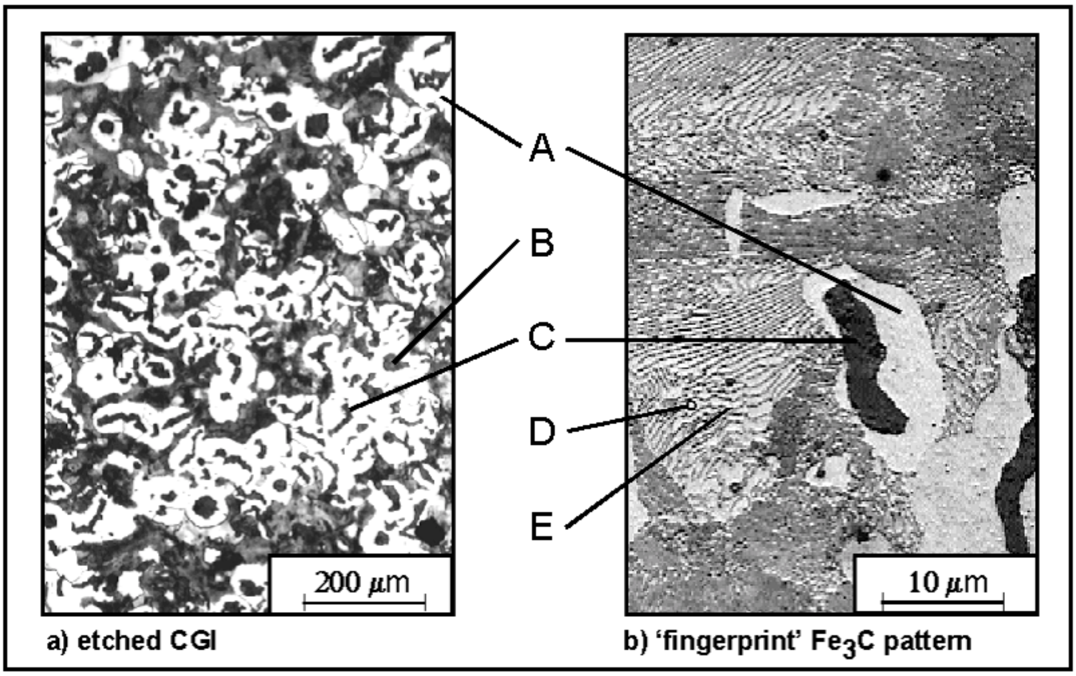


Figure 7: The pearlite phase is an ordered layering of ferrite and Fe_3C plates (A: free ferrite, B: pearlite, C: graphite, D: ferrite band, E: Fe_3C plate)

These two basic pearlite contents have since been widely evaluated in terms of engine performance, durability and machinability. As yet, however, the necessary pearlite content to simultaneously optimize machinability, engine performance and foundry production has not been determined. A series of comparative milling and turning tests were therefore conducted over the range of 50 to >95% pearlite to determine the machinability of conventional (<10% nodularity) compacted graphite irons. The pearlite content was stabilized only by the addition of copper and tin for this first series of tests. The use of stronger pearlite stabilizers to effectively produce 100% pearlitic matrices is addressed later in this section. The microstructure and chemical details of the milling and turning test pieces are summarized in Table V. The pearlite content of the test pieces is grouped into low (50- 60%), medium (70-80%) and high (>95%) pearlite categories. The pearlite contents are stated as ranges rather than exact values to reflect both the practical microstructure variations under production conditions and the subjectivity of pearlite evaluation. Likewise nodularity values are presented in 5% increments rather than exact values. Ultimately, the data from Table V are plotted at the midpoint values of 55% pearlite, 75% pearlite and 97.5% pearlite in Figure 8 for carbide machining and in Figure 9 for PCBN machining. The cutting conditions were as presented in Table II.

Table V
Microstructure and chemistry details for the evaluation of milling and turning as a function of perlite content

Carbide Or CBN	Turning Or Milling	Microstructure		Chemistry (%)									
		% Pearlite	%Nod	C	Si	Mg	Cu	Sn	Mn	Sb	S	Ti	Cr
Both	Turning	50-60	5-10	3.76	2.21	0.012	0.43	0.029	0.40	0.004	0.011	<0.01	0.02
Both	Milling	50-60	<5	3.73	2.25	0.009	0.45	0.031	0.40	0.003	0.011	<0.01	0.03
Both	Turning	70-80	<5	3.73	2.25	0.011	0.46	0.033	0.40	0.004	0.015	<0.01	0.03
Both	Milling	70-80	5-10	3.74	2.17	0.009	0.43	0.036	0.41	0.004	0.014	<0.01	0.03
Both	Turning	>95	<5	3.64	2.19	0.013	0.75	0.090	0.39	0.005	0.014	<0.01	0.03
Both	Milling	>95	5-10	3.77	2.23	0.008	0.79	0.100	0.38	0.003	0.012	<0.01	0.02

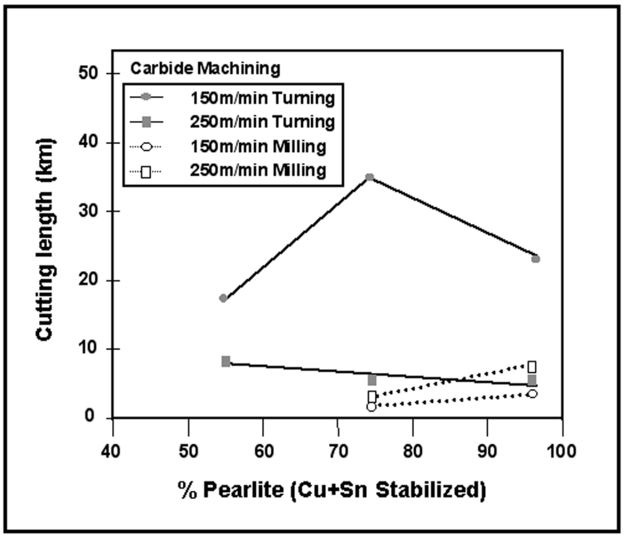


Figure 8: The effect of pearlitic content on tool life during carbide milling and turning. The pearlite was stabilized by additions of copper and tin

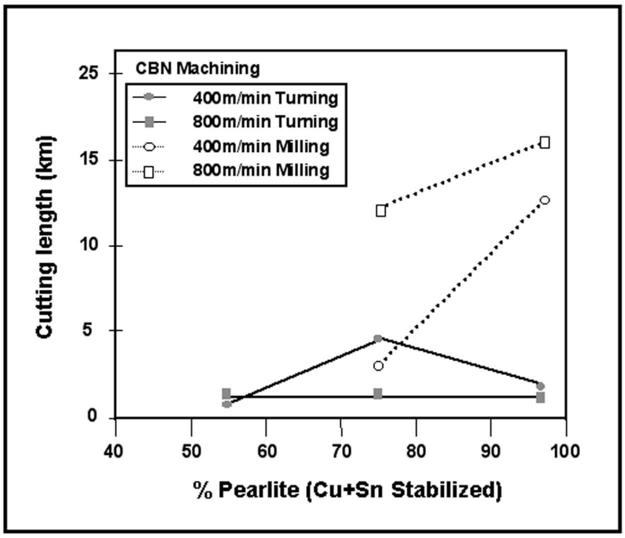


Figure 9: The effect of pearlitic content on tool life during CBN milling and turning. The pearlite was stabilized by additions of copper and tin

The results of the copper-plus-tin stabilized pearlite milling and turning tests in the 50 to >95% pearlite range can be summarized as follows:

- Milling improves with increasing pearlite. An increase from 70-80% pearlite to >95% pearlite improves carbide tool life by a factor of 2-3 and PCBN tool life by a factor of 1.5-3. The improvements in tool life are at the high end of these ranges for the lower speeds tested (150 m/min for carbides and 400 m/min for PCBN) and at the low end of the range for the higher speeds tested (250 m/min for carbide and 800 m/min for PCBN).

- Over the range of 50 to >95% pearlite, the turning tool life at the lower speeds tested (150 m/min for carbides and 400 m/min for PCBN) shows a maximum at 75% pearlite. This result was validated by two separate batches of CGI cylinders produced in the 70-80% pearlite range.

- The turning tool life at the higher speeds tested (250 m/min for carbides and 800 m/min for PCBN) is entirely unaffected by pearlite variations within the range of 50-97.5% pearlite.

Within the practical range of 50-97.5% pearlite, increasing pearlite contents improve the milling tool life but decrease the tool life in turning operations. Additionally, the positive effect on milling is stronger than the negative effect on turning. Unfortunately, this opposite behavior makes it impossible to define an optimal pearlite content for all machining operations. Presumably, the low pearlite alloys are too soft and deformable for easy cleavage and chip formation during milling while the high pearlite alloys are too hard and abrasive for continuous cutting. While it is not possible to define an optimal pearlite content for all operations, it may be possible to specify a pearlite content to alleviate a specific bottleneck in the production process.

Additional alloying with antimony and manganese were investigated in the present study to achieve an effectively 100% pearlitic structure in order to determine if the 1-5% of free ferrite present in the Cu-Sn stabilized CGI was responsible for the increased tool wear during PCBN machining. These tests were motivated by the observation that small amounts of free ferrite can significantly reduce PCBN tool life in grey cast iron. It was therefore hypothesized that a similar mechanism may be preventing PCBN from realizing its full potential in CGI machining. According to the initial constraints of this study, the fully pearlitic CGI was also evaluated with carbide tools to ensure that any potential improvements in PCBN performance were not offset by simultaneous reductions in the life of carbide inserts.

Antimony (Sb) is up to one hundred times stronger than copper and at least twice as strong as tin in terms of pearlite stabilization [3]. Additions of approximately 0.1% Sb are usually sufficient to stabilize a fully pearlitic matrix, particularly in the presence of copper, tin or manganese additions. Three separate one-tonne ladle batches of Sb-CGI were produced to evaluate the effect of antimony stabilization on machinability. The microstructure and composition of the Sb-CGI test cylinders is summarized in Table VI.

Table VI

Microstructure, chemistry and mechanical properties of the Sb-CGI test cylinders

Batch Number	Microstructure		Chemistry (%)						Properties			
	% Pear	% Nod	C	Si	Cu	Sn	Mn	Sb	UTS (MPa)	E_o(GPA)	% Elong	BHN
1	>98	<5	3.64	2.20	0.53	0.003	0.39	0.080	421*	133*	3.0*	235
2	>95	<5	3.67	2.19	0.29	0.003	0.41	0.085	431	-	1.6	233
3	100	<5	3.68	2.24	0.29	0.003	0.41	0.099	465	-	0.7	258

* Note: Tensile bar obtained from machining test cylinder. Others obtained from 25 mm dia test bar

Table VII

Microstructure and chemistry details of the Mn-CGI test cylinders

Microstructure		Chemistry (%)									
% Pearlite	% Nodularity	C	Si	Mg	Cu	Sn	Mn	Sb	S	Ti	Cr
100	5-10	3.67	2.17	0.011	0.83^{S}	0.081	0.89	0.003	0.012	0.008	0.02

Manganese contents in CGI typically range from 0.30- 0.45% Mn. In the presence of 0.6-1.0% copper and 0.06-0.1% tin, additional manganese can be sufficient to increase the pearlite content to 100%. Therefore, manganese additions were also evaluated to determine the effect of ferrite-free microstructures on CGI machining. The composition of the Mn-CGI test cylinders is provided in Table VII. Note that the base copper and tin contents are sufficient to achieve >95% pearlite in the presence of normal (0.40%) manganese.

The Sb-CGI and Mn-CGI variants were evaluated by carbide and PCBN turning under the conditions originally presented in Table II. The turning results are presented in Figure 10 as extensions of the copper-plus-tin stabilized CGI plots previously shown in Figures 8 and 9. The Sb-CGI test cylinders from Batch No. 1 (Table VI) are plotted at 99% pearlite while the Mn-CGI test cylinder results are plotted at 100% pearlite.

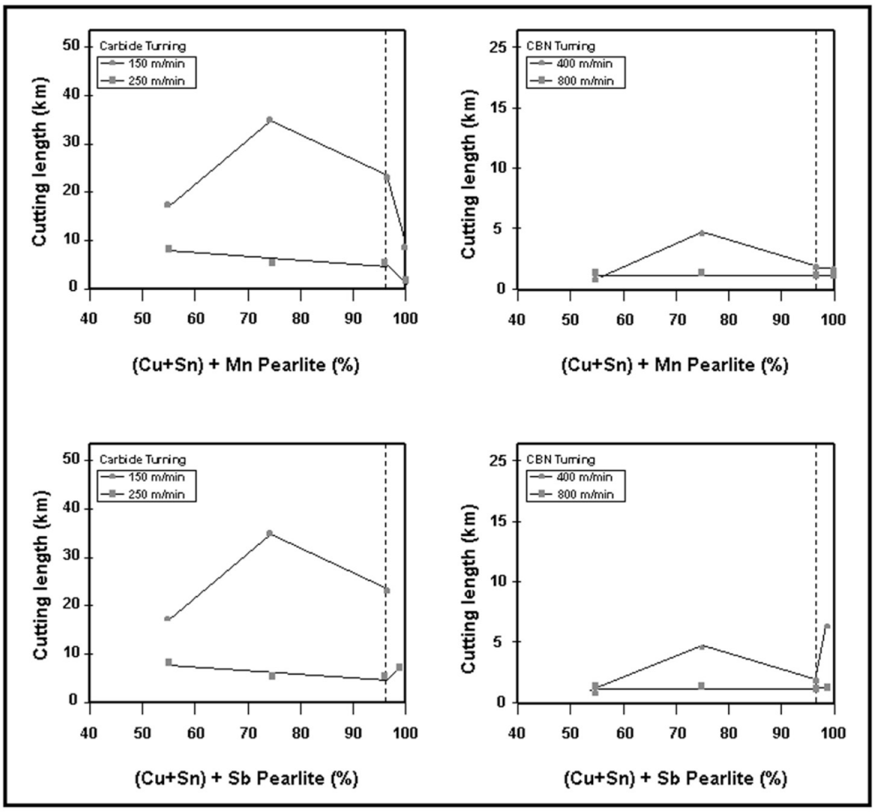


Figure 10: The effect of an incremental increase from 97.5% pearlite (Cu+Sn) to 99% (Sb-CGI) and 100% (Mn-CGI) pearlite on tool life during carbide and CBN turning

The results shown in Figure 10 indicate that:

- Manganese stabilization to 100% pearlite does not affect PCBN tool life

- Manganese stabilization to 100% pearlite increases carbide tool wear by 50-100%. The effect is more severe at 150 m/min than at 250 m/min.

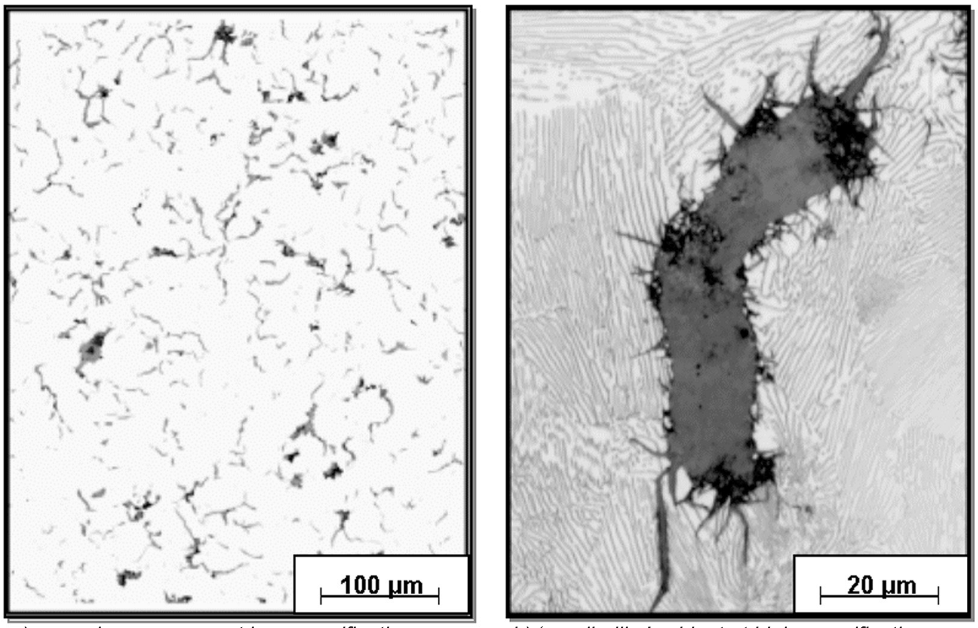
- The use of antimony to increase the pearlite content from 97.5% to 99% provides a slight increase in tool life at the lower speeds tested for turning (150 m/min for carbides and 400 m/min for PCBN). However, the Sb-CGI tool life remains lower than or approximately equal to that observed at the lower (75 and 55%) pearlite levels.

- Antimony alloying to achieve 100% pearlite does not provide any benefit to the tool life during high speed (800 m/min) turning with PCBN. The 800 m/min PCBN tool life is unaffected by pearlite content over the entire range from 50-100% pearlite.

Overall, it can clearly be concluded that small amounts of free ferrite in a predominantly pearlitic matrix are not responsible for the accelerated wear of PCBN inserts during the machining of CGI.

While the results shown in Figure 10 indicate that Sb-alloying to achieve 100% pearlite may have provided an increase in tool life during carbide turning at 250 m/min and PCBN turning at 400 m/min, it is more likely that the entire curve is shifted by the excess additions of antimony or manganese and that the plot provided in Figure 10 only shows the final data point. This uncertainty prompted further analysis of the Sb-CGI microstructure which indicated that any improvement in machinability may have been caused by a degeneration of the graphite particles rather than an increase in pearlite content. When viewed at 100x magnification, (Figure 11 (a)) the CGI microstructure looks 'normal'. However, at 500x magnification (Figure 11 (b)) distinct graphite spikes can be seen on the surface of the graphite particles. It appears that gaps in the Sb diffusion barrier allow carbon atoms to attach to the graphite and the subsequent growth from these contact points results in the formation of discrete graphite spikes. The spiky graphite was found to be common to all three Sb-CGI heats presented in Table VII.

Mechanical property testing has subsequently shown that the Sb-CGI has a tensile strength of 421-465 MPa which is lower than the approximately 500-525 MPa that would be expected from an effectively 100% pearlitic CGI cast in a 25 mm diameter test bar. Uniaxial tension-compression fatigue tests have also shown that the Sb-CGI variants have approximately 6% lower fatigue limit than a conventionally alloyed pearlitic CGI. Although these decreases in mechanical properties are not dramatic, the simultaneous absence of any real benefit in tool life clearly shows that there is no practical reason for adopting Sb-alloying of CGI.



a) normal appearance at low magnification *b) 'needle-like' evident at high magnification*

Figure 11: The use of antimony for pearlite stabilization causes spikes on the graphite particles

The Effect of Sulphur

Beyond the obvious differences in graphite shape and material properties, the most significant difference between grey iron and CGI is the sulphur content. Grey cast irons typically contain 0.08-0.12% sulphur. However, because compacted graphite particles are only stable at low oxygen and sulphur contents, CGI is produced in the range of 0.005-0.025%S. The approximate ten-fold decrease in sulphur content, combined with the surprisingly poor machinability of the 50/50 flake/CGI alloy produced from a typical desulphurized CGI base iron, prompted an investigation into the role of sulphur in order to explain the difference between the high speed machinability of CGI and grey iron.

In grey cast iron, the sulphur reacts with manganese to form manganese sulfide (MnS) inclusions, which are generally less than 10 µm in size. Similar to the so called free-machining steels, the presence of the soft and pliable MnS inclusions can potentially lubricate or even form protective layers on the cutting edges of the inserts. In contrast to grey iron, however, CGI is produced by adding magnesium to the liquid iron to consume both sulphur and oxygen. Because magnesium is a very strong sulfide former, magnesium sulfide (MgS) inclusions are formed preferentially to manganese sulfide (MnS). The deoxidizing effect of magnesium also leads to the presence of magnesium oxide (MgO) and magnesium silicate (xMgO • $ySiO_2$) inclusions in CGI. The tests conducted to determine the effect of sulphur can therefore be regarded as an evaluation of the influence of strong and hard magnesium sulfide and magnesium silicate inclusions in CGI versus the soft and pliable MnS inclusions in grey iron.

The difference between CGI and grey iron was evaluated in single-insert PCBN turning tests at 10, 100, 400 and 800 m/min. At the low cutting speeds of 10 and 100 m/min, no significant difference could be observed in the wear behaviour or projected tool life for either grey iron or CGI. However, as the cutting speed increased to 400 m/min a built-up layer containing manganese and sulphur began to form on the cutting edge of the grey iron insert. This layer became thicker and denser as the cutting speed increased to 800 m/min. In contrast, no layers of any type were able to accumulate on the CGI insert. The presence of an MnS layer on a grey iron insert and an abrasively worn flank on a CGI insert are shown in Figure 12 to illustrate this difference. As a result of the formation of a protective layer, the grey iron tool life increases with increasing cutting speed. This counter-initiative behavior is presumably due to the growth and densification of the protective MnS layer. In contrast to this unique behavior observed in grey cast iron, other materials such as steels, ductile iron and CGI exhibit the expected behavior of decreasing tool life with increasing cutting speeds.

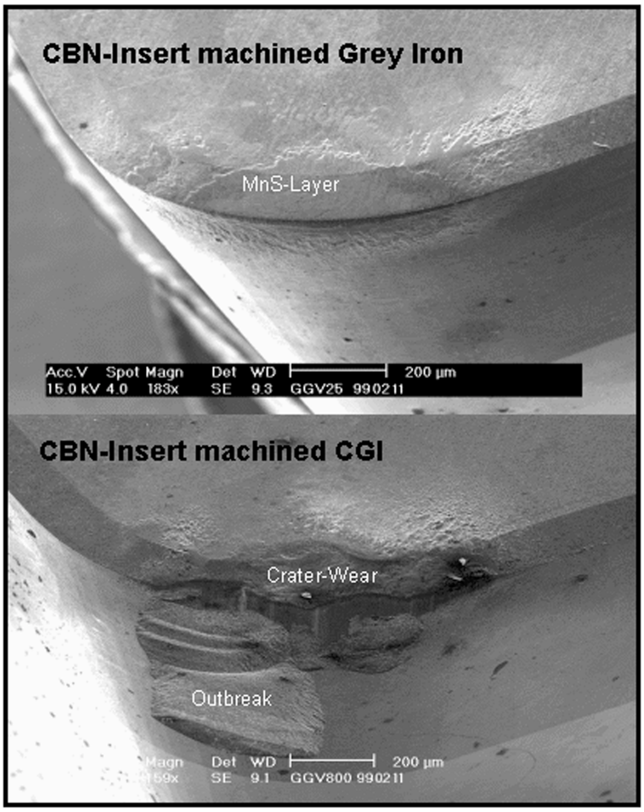


Figure 12: Protective MnS layers form on the cutting edge of PCBN inserts when cutting grey iron at high speeds. In contrast, inserts used for CGI exhibit abrasive wear

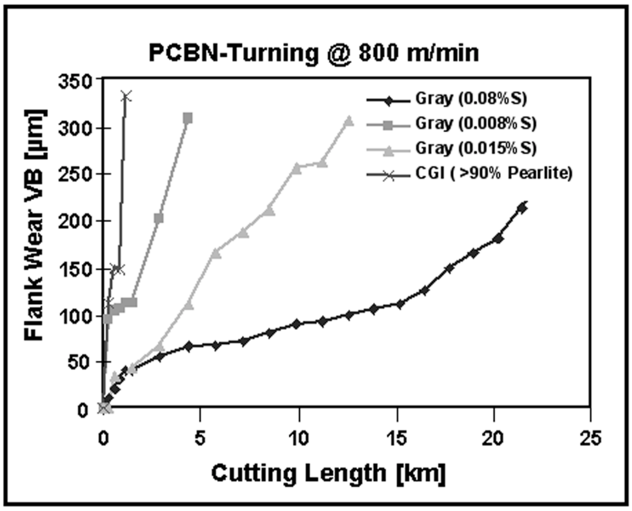


Figure 13: The machinability of grey cast iron gradually decreases as the sulphur content is reduced from, normal grey iron levels (0.08%S) to normal CGI levels (0.008%S)

The absence of a protective layer when machining CGI can potentially account for much of the difference in tool life during high speed boring operations. To validate this theory, a series of comparative turning trials were conducted with grey iron specimens produced with low sulphur contents. The results of these tests are shown in Figure 13 for PCBN turning at 800 m/min. The plot shows the development of flank wear as a function of cutting length for the standard reference materials (grey iron and CGI presented previously in Table IV and Figures 4 and 5) and two grey iron materials produced with lower sulphur contents.

The results presented in Figure 13 clearly show that the grey iron tool life is halved as the sulphur content is reduced from the standard level of 0.08%S to 0.015%S, and halved again with a further decrease from 0.015%S to 0.008%S. The remaining difference in tool life between the 0.008% grey iron and the standard CGI reference (0.012%S) can be accounted for by the differences in mechanical properties. It is therefore proposed that the approximately ten-fold difference in tool life between CGI and grey iron during high speed continuous cutting operations is primarily accounted for by the presence of a protective MnS layer during the machining of grey cast iron. The remaining differences in tool life may be accounted for by the commensurate differences in mechanical properties.

The sulphur results obviously prompted an investigation into the ability to stabilize MnS inclusions in magnesium treated CGI. Efforts were made to produce high-sulphur CGI and to mechanically add MnS powders immediately prior to casting. However, the strong thermodynamic affinity of magnesium for sulphur prevented MnS from forming in the high sulphur tests and quickly reduced the added MnS powders to MgS. Scanning electron microscope EDAX analyses showed that the reaction kinetics were so fast that it was even impossible to generate MnS inclusions during in-mold addition of magnesium to high sulphur base irons or in-mold additions of MnS powders to normal CGI base irons.

Effect of Titanium

Titanium is typically present in cast irons in the range of 0.005-0.02% Ti. The titanium reacts with carbon and/or nitrogen present in the molten iron to form hard titanium carbonitride (Ti(C,N)) inclusions that are actually harder than tungsten carbide, a common tool material. As the Ti(C,N) inclusions form in the liquid state they are free to grow with a cubic shape according to their atomic crystal structure. As shown in Figure 14, the individual 1-5 μm inclusions may cluster together to form larger agglomerates.

The titanium content of cast iron is determined either by the raw materials or by intentional alloying. In some applications, for example brake components or cylinder liners, titanium may be intentionally added to form carbonitride inclusions to improve wear resistance. In the case of compacted graphite iron, larger amounts of titanium have historically been used to prevent the formation of nodular graphite and thus increase the stable magnesium range for CGI production.

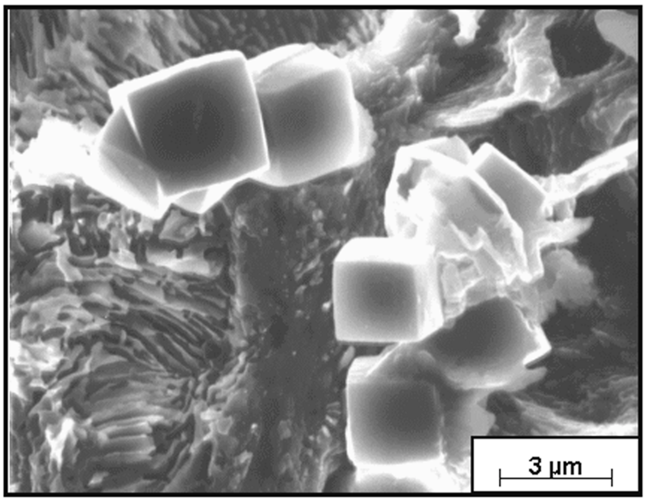


Figure 14: Cubic titanium carbonitride inclusions are harder than tungsten carbide and significantly increase abrasive tool wear

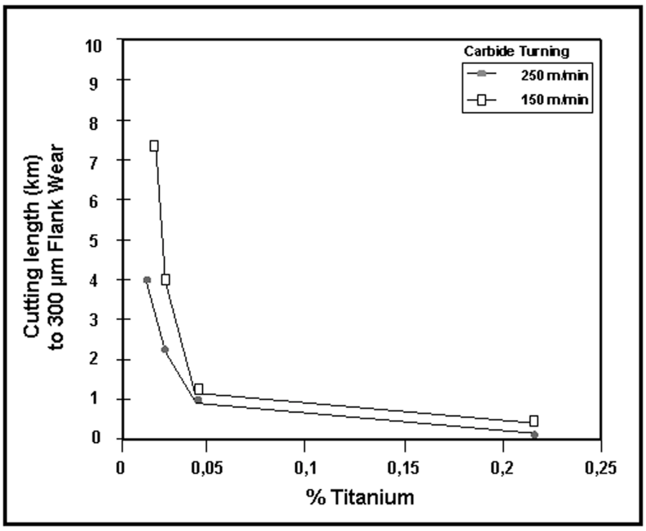


Figure 15: The addition of titanium dramatically reduces the tool life of compacted graphite iron during carbide turning

The titanium content of CGI can be broadly accounted for as follows:

% Ti	Metallurgical Explanation
0.005–0.02	Typical trace level
0.04 – 0.07	Intentional addition to improve wear resistance
0.10 – 0.25	Intentional addition to increase stable production of CGI

The effect of titanium on tool wear was evaluated in carbide turning tests at 150 and 250 m/min (Table II). The cutting length results are shown in Figure 15 for the specimens listed in Table VIII.

Table VIII
Microstructure and chemistry of the Ti-CGI test cylinders

Microstructure		Chemistry (%)									
% Pearlite	% Nodularity	C	Si	Mg	Cu	Sn	Mn	Sb	S	Ti	Cr
90-95	5-10	3.46	2.35	0.011	0.86	0.08	0.26	**	0.008	0.01	**
90-95	<5	3.50	2.32	0.012	0.91	0.090	0.29	0.006	0.013	0.04	0.04
80-90	<5	3.60	2.22	0.011	0.80	0.087	0.39	0.005	0.009	0.22	0.04

** Note: Chemistry not available, although ‘normal’

The machining results clearly show the powerfully negative effect of titanium additions on the machinability of CGI. Slight increases in the trace level of titanium from 0.01 to 0.02% are sufficient to reduce the tool life by approximately 50%. Further additions to 0.04% Ti (wear resistance levels) and 0.22% Ti (CGI stabilization levels) render the material effectively unmachinable during carbide turning. This result reinforces the importance of inclusions in determining the machinability of cast irons.

Following the results of the fixed insert carbide machining, a second series of Ti-CGI machining tests were conducted with a machining tool which used rotating inserts [4]. This test was conducted to determine if the more robust rotary concept would be better able to withstand the Ti-CGI. The standard 27 mm diameter silicon nitride rotary inserts were used at a cutting speed of 800 m/min, 0.3 mm/rev feed and 0.15 mm depth of cut. The end-of-life criteria was defined as 300 μm flank wear. These tests showed that the rotary tool life at 0.22% Ti was 50 times less than it was when used with 'normal' trace levels of CGI (the 0.02 and 0.04% Ti-CGI variants were not tested with the rotary concept).

The frictional heat generated in the rotary tests was so severe that it liquidified the bearing grease in the rotary cartridge requiring re-lubrication after each cutting pass of the test cylinder.

It is evident that titanium additions seriously reduce the machinability of CGI. The hard Ti(C,N) inclusions increase abrasive wear and, as such, have exactly the opposite effect of the soft and lubricating MnS inclusions found in grey cast iron. While titanium additions may be tolerated in components with limited machining requirements, for example, exhaust manifolds and brackets, the titanium level in extensively machined components must be controlled as low as possible in order to optimize tool life.

The Effect of Chromium

Chromium is introduced to cast irons either through the steel charge material or by intentional alloying to provide strength at elevated temperatures, for example in cylinder head applications. Chromium stabilizes pearlite in the same way as manganese, by increasing the solubility of carbon in austenite. However, chromium is a more potent pearlite former. In comparison to manganese, the increased potency of chromium produces a finer pearlite structure thus increasing the Fe_3C content of the pearlite and suppresses graphite nucleation thus increasing the risk of carbides and chill [5]. Additionally, chromium segregates strongly during solidification thus promoting carbide formation in the last areas to solidify. This formation of segregation carbides is assisted by the fact that chromium atoms can substitute for irons atoms in the normal Fe_3C iron carbide lattice to form $(Fe,Cr)_3C$. This substitution results in a very stable carbide that, at chromium levels in excess of 0.1%, can even prevent its transformation to ferrite during annealing operations.

The effect of chromium additions on the machinability of CGI was evaluated during the manganese and antimony tests previously presented in Figure 10 as a means of stabilizing a 100% pearlitic matrix. During these tests the addition of chromium effectively doubled the tool wear during carbide turning at 150 m/min and, as such, was similar to the effect of manganese. Prior to the laboratory based trials, however, the influence of chromium on the machinability of CGI was indicated when comparing the tool life results from two separate transfer line trials conducted by Ford Motor Company with Zetec cylinder blocks. The CGI cylinder blocks in the first trial contained >85% pearlite wherein the pearlite was stabilized by manganese and chromium additions. In response to the unexpectedly high tool wear, the second trial was conducted with 70-85% pearlitic CGI, however, in this trial the pearlite was stabilized by additions of copper and tin. The mean chromium level was reduced from approximately 0.18% in the first trial to approximately 0.10% Cr for the second trial. The basic chemistry and relevant microstructural details for the two trials are summarized in Table IX.

Table IX
Pearlite stabilization and microstructural details
for the two different transfer line trials

Trial Number	Chemistry Ranges (%)				Microstructure		
	Cu	Sn	Mn	Cr	% Pearlite	% Carbides	Chill
1	0.30-0.35	0.03-0.04	0.40-0.50	0.08-0.23	>85	2-3	Present
2	0.55-0.60	0.05-0.06	0.25-0.35	0.06-0.12	70-85	<1	None

The reduced chromium content used in the second transfer line trial provided an approximate 40% improvement in the overall machinability of CGI. While this may in part be due to the reduced pearlite content, the most significant factor is the elimination of chill and segregation carbides due to the reduced chromium level. As the basic machinability of CGI is more difficult than that of grey iron, the prevention of chill and segregation carbides in CGI is even more critical. Restricting the chromium to trace levels (<0.08% Cr) is therefore important for the optimal machinability of CGI.

Inclusion Engineering

All cast metals contain non-metallic inclusions. The individual inclusions are generally in the size range of 0.1-10 µm and are either oxides, nitrides, sulfides or complex intermetallics. A typical tonne of cast iron may contain 10^{10} inclusions. Depending on their composition, these inclusions can either be hard and abrasive (for example TiC) or soft and pliable (for example MnS). The objective of inclusion engineering is to treat the molten iron with alloying elements that modify the chemical composition of the existing inclusions to change them from hard to soft. Inclusion engineering is widely practiced in steel metallurgy, for example by increasing sulphur to form MnS or by adding calcium to modify the hard alumina inclusions to softer calcium-aluminates.

An attempt was made in the present study to generate soft and pliable inclusions in CGI by modifying the addition sequence of magnesium and inoculant during base treatment. Under normal circumstances, the addition of magnesium results in a predominance of relatively hard magnesium-silicate and magnesium sulfide inclusions in CGI melts. The present experiment substituted the initial addition of magnesium with relatively large additions of calcium and aluminum during furnace tap. The intent of these additions was to consume the available oxygen by generating calciumaluminate inclusions (which are known to be relatively soft) and thereafter adding a reduced amount of magnesium. Although the trial succeeded to produce calcium-bearing inclusions, it did not provide any significant improvement in tool life. Carbide turning tests conducted at 200 m/min, 0.2 mm/rev and 1.5 mm depth of cut showed approximately 20% improved tool life relative to ‘normal’ CGI, however, no improvement was observed at either 250 or 400 m/min. Improvements of 5-10%10% were also observed during PCBN turning at 400 and 800 m/min, however, these gains alone cannot overcome the considerable tool life differences between CGI and grey iron. In consideration of the marginal machining improvements and the large increase in the complexity and cost of the necessary CGI production process, the inclusion engineering trials were discontinued.

Beyond the conventional concept of inclusion engineering, which is to transform abrasive inclusions into soft inclusions, a secondary objective of inclusion engineering is to generate inclusions that are able to accumulate on the cutting insert to form a protective layer. Investigation of the used inserts from the inclusion engineering trials did not show any build-up of inclusions on the flank surface. However, it is herein proposed that the accumulation of a protective layer on the insert not only depends on the inclusion composition but also the cutting mechanism.

High speed filming of grey iron machining [6] reveals that the brittle nature of grey iron causes the cleavage to occur ahead of the cutting edge of the insert. Although these films are obtained at low (<10 m/min) cutting speeds, the net result is that the flank and top surfaces of the insert frequently pass through the material without any abrasive contact. During these ‘contact-free’ periods, any inclusions that have come into contact with the insert have the opportunity to adhere and sinter to the tool (or each other) before the next abrasive contact with the work piece. In this way, an accumulation can develop. In contrast, the ductile nature of CGI results in a more continuous and abrasive contact between the insert and the work piece thus preventing the inclusions from accumulating on the surface. While this may explain the different accumulation behaviour, it must be noted that manganese sulfide inclusions do accumulate on cutting inserts during the low speed (<200 m/min) continuous cutting of carbon and stainless steels. With steels, however, the accumulation of non-metallics on the cutting edge stops as the cutting speed is increased and abrasive wear begins. The different behaviour in the formation and growth of the protective layer in grey iron and steels may be accounted for by the difference in ductility and chip formation at the cutting edge of the insert.

The accumulation of a protective inclusion layer occurs when both the composition of the inclusion population and the cutting mechanism are favorable. The ability of inclusion engineering to enhance the formation of a protective layer is evident from another study shown in Figure 16 [7] where the use of an inoculant containing 2-3% calcium in grey iron results in the formation of complex $CaO \cdot Mn_2O_3 \cdot SiO_2$ inclusions. Within this calcium range the inclusion consistency optimizes adhesion to the TiC coating of the insert resulting in a minimum flank wear. However, inclusions of non-optimal composition, for example at 10% Ca content in Figure 16, can actually result in increased flank wear. These results again show the importance of inclusions, and more importantly, their hardness and properties. Unfortunately, it is not possible to directly transfer the $CaO \cdot Mn_2O_3 \cdot SiO_2$ technology to CGI. The necessary addition of magnesium during the production of CGI, which is a stronger oxide former than either manganese or silicon, dictates the chemical composition of the inclusions. The possibility to generate favorable inclusions is much less in CGI than in either grey iron or steel due to the predominating thermodynamic strength of magnesium.

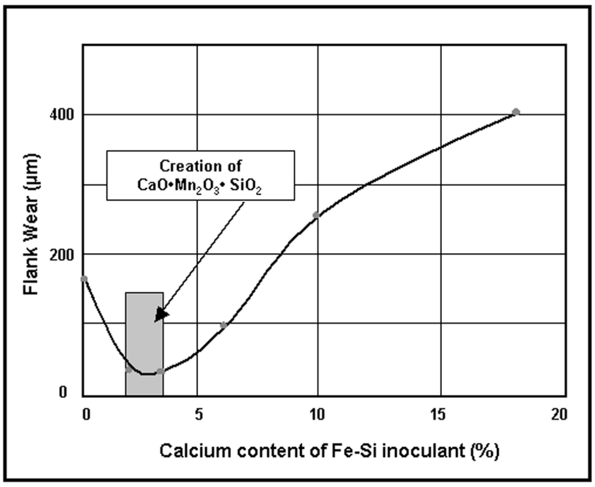


Figure 16: A grey iron inoculant containing 2-3% calcium optimizes the ability to form a protective layer on a TiC coated insert [7]

The Effect of Silicon

While copper, tin, manganese and antimony are pearlite stabilizers, silicon promotes ferrite formation. Compacted graphite iron typically contains 2.0-2.4% silicon, together with intentional additions of pearlite stabilizers to achieve the desired pearlite level. However, if the pearlite stabilizers are reduced to trace level and the silicon content is increased to 3.0% or more, the CGI will have a predominantly ferritic matrix. Although the matrix is ferritic, the increased silicon concentration hardens and embrittles the ferrite phase by a solid-solution hardening mechanism resulting in a fully ferritic CGI that can have the same hardness level and tensile strength as pearlitic grey iron or even pearlitic CGI.

The use of high-silicon ferritic cast irons was first advocated for ductile irons [8] where it was found that high-silicon ductile iron could have the same average hardness as conventional 50-75% pearlitic ductile irons, but, because the matrix was consistently ferritic, the hardness variation was much smaller. Ultimately, the consistency of the hardness arriving at the machining line resulted in less tool wear and less downtime. The high-silicon ductile iron wasn't necessarily easier to machine, it was simply more consistent. In order to determine if high silicon additions could have a similar effect on the machinability of CGI, a series of turning test pieces were produced and machined. The microstructure, hardness and composition of the test pieces are summarized in Table X. The PCBN and carbide turning results for the high silicon CGI are compared to the initially tested copper-plus-tin stabilized pearlitic CGI (Table V and Figures 8 and 9) in Figure 17.

Figure 17 shows that a 3% silicon CGI alloy provides substantially improved tool life during PCBN turning at 400 m/min and during carbide turning at 150 and 250 m/min. Although the 3% silicon alloy may find several good product applications, it is relatively soft (BHN 170) and would likely not satisfy cylinder bore wear requirements. Additionally, the 3% silicon alloy was unable to provide any significant improvement during PCBN turning at 800 m/min, which is the most critical operation for cylinder boring. Further development of the 3% silicon alloy was therefore put 'on-hold'.

Table X
Microstructure and chemistry details of the high-silicon CGI test cylinders

Microstructure		BHN (5/750)	UTS (MPa)	Chemistry(%)									
% Pearlite	% Nodularity			C	Si	Mg	Cu	Sn	Mn	Sb	S	Ti	Cr
<2	10-20	170	386	3.55	3.02	0.007	0.05	0.006	0.18	0.005	0.010	0.013	0.02
<2	5-10	202	450	3.02	4.03	0.010	0.06	0.005	0.34	0.005	0.013	0.014	0.03

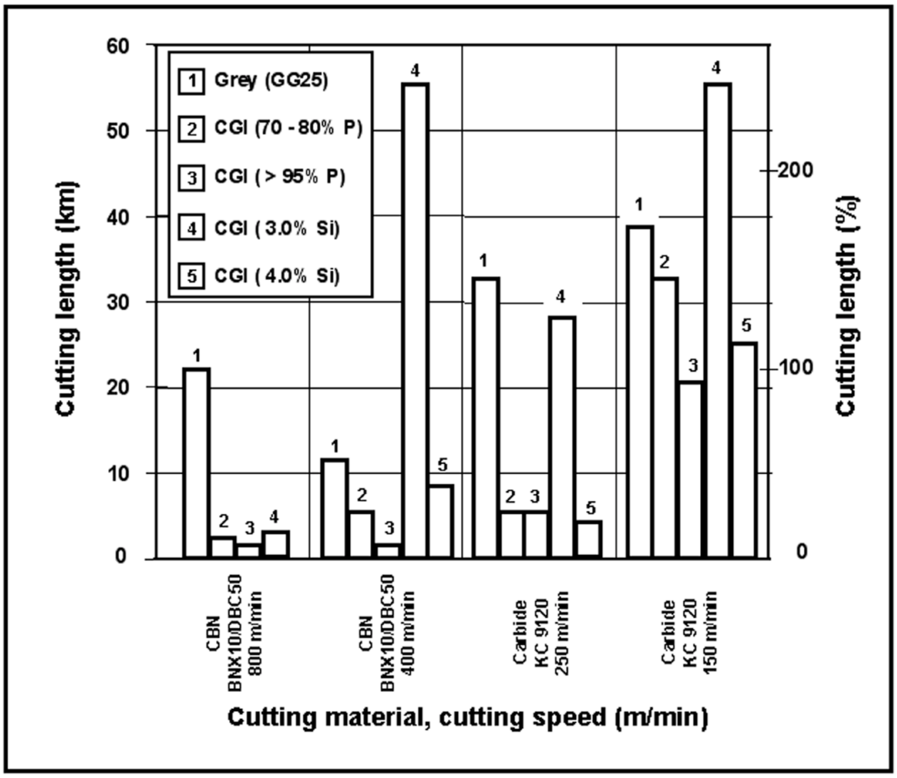


Figure 17: The effect of silicon content on CGI tool life during CBN and carbide turning

An additional increase in the CGI silicon content to 4% (Table X) increases the bulk hardness into the normal range for grey iron cylinder blocks and makes it a more viable candidate material. However, at this silicon level, the previously obtained improvements in the carbide tool life are lost. The only remaining improvement is in PCBN turning at 400 m/min. While the improved tool life during PCBN machining at 400 m/min merits further consideration, this alloy did not satisfy the original program constraints of minor changes not requiring repetition of the CGI development cycle. This is particularly true of concerns surrounding the wear behaviour and fatigue properties of a fully ferritic cylinder block. Silicon additions are also known to reduce the thermal conductivity of ductile irons. Parallel testing of thermal conductivity was therefore undertaken to evaluate this potential effect on the high-silicon CGI materials. These tests showed that the thermal conductivity of the 4% Si alloy is 31.7 W/m-K at 100°C compared to approximately 35 W/m-K for the 3% Si alloy, 37 W/m-K for 'normal' CGI and approximately 48 W/m-K for conventional grey cast iron. This additional loss of approximately 15% thermal conductivity relative to 'normal' CGI limits the potential of the 4% silicon alloy in the thermally loaded applications such as cylinder blocks and heads. Despite the very promising initial results with the 3% silicon alloy, further development of the high-silicon CGI alloys was abandoned.

CGI Tooling Concepts

The investigation of metallurgical variables has shown that good control of the graphite microstructure and the absence of harmful elements such as titanium and chromium, can contribute to the successful machining of CGI. However, these parameters alone cannot resolve the difficulties associated with high speed cylinder boring. Additionally, the very positive development of a protective MnS layer in grey cast iron cannot be transferred to CGI due to the instability of MnS in magnesium treated iron or the instability of the compacted graphite particle shape in the presence of high sulphur contents. For these reasons, considerable effort has been expended toward the development of novel tooling concepts for cylinder bore roughing and finishing.

Building on the relatively good tool life provided by carbide inserts, several machine tool companies have recently proposed CGI boring tools containing multiple carbide inserts. Although the cutting speed is restricted to the carbide range of 100 m/min, the presence of multiple inserts allows for higher feed rates. The net result allows for the removal of 2-3 mm of stock material during rough boring with a cycle time of less than 14 seconds. Some examples of multiple insert cylinder boring tools are shown in Figure 18.

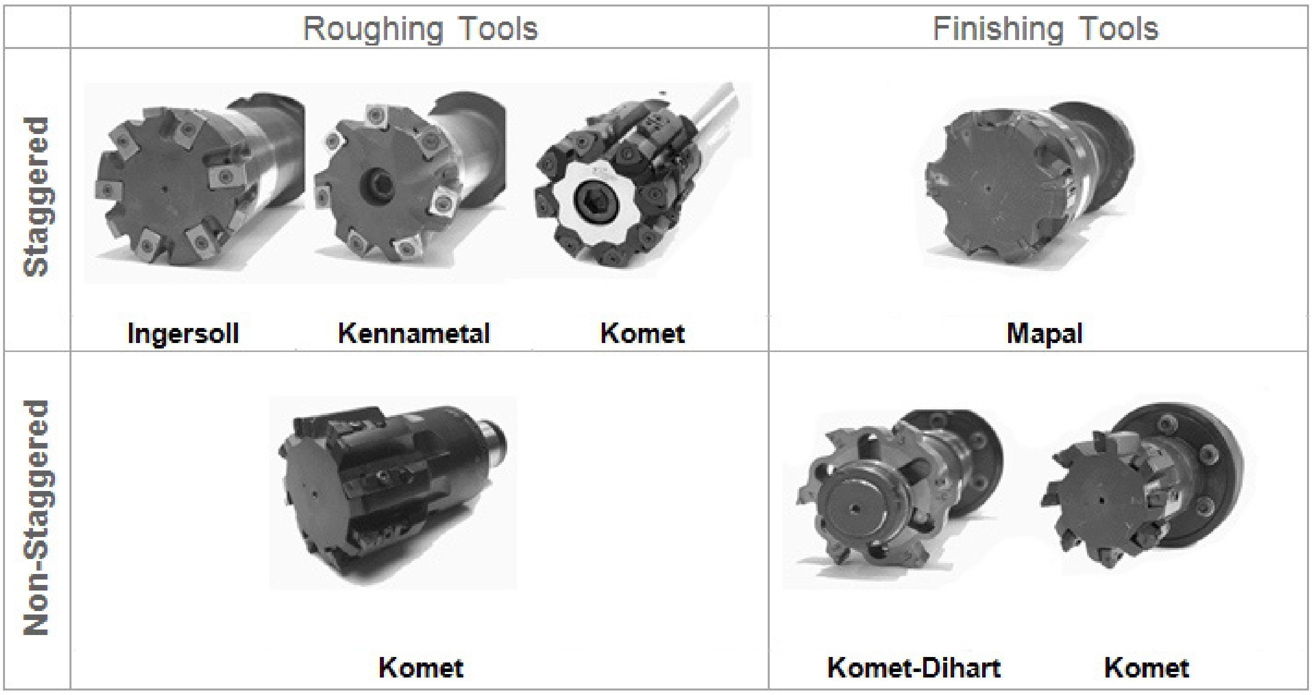


Figure 18: Cutting tools with multiple carbide inserts satisfy dimensional and productivity requirements for CGI cylinder bore roughing and finishing

In general, two different types of multiple insert tools have been developed. The first type relies on staggered inserts wherein some of the inserts make a relatively deep primary cut while the remaining axially staggered inserts make a more shallow secondary cut. This concept protects the final inserts and allows the tool to maintain geometry and roughness requirements for an entire eight hour production shift. Tools without staggering have also been developed and have equally shown the ability to satisfy grey iron cycle times and geometry and roughness criteria by simply sharing the workload among several inserts.

The multiple insert concept has also been successfully demonstrated for cylinder bore finishing operations. In this case, for the staggered tools, the first series of inserts would remove approximately 200 μm of material while the second series of axially staggered finishing inserts would remove only about 20 μm. Again, the multiple insert concept allows for high feed rates that satisfy grey iron transfer line cycle times while the use of either staggered or non-staggered principles allows the tool to maintain dimensional tolerances over prolonged periods.

The laboratory-based machining trials conducted with CGI cylinder blocks have shown that roughness, geometry, productivity and tool life criteria can all be satisfied with these new tooling concepts. Other novel tooling concepts, including the use of rotating inserts [4] or milling-type helical cutters for 'mill-boring' [9] are also being developed to replace conventional high speed single-insert PCBN machining for the critical cylinder boring operation.

Conclusions

With at least 75% higher strength, 40% higher elastic modulus and approximately double the fatigue strength, it is evident that compacted graphite iron will be more difficult to machine than grey cast iron. During carbide milling and turning operations the reduction in tool life is commensurate with the increase in mechanical properties. However, during high speed continuous cutting operations such as PCBN or ceramic turning and boring, the CGI tool life can be 10-20 times less than that of grey iron. The present study has shown that the manipulation of metallurgical parameters alone is not sufficient to improve the high speed machinability to grey iron levels. Nonetheless, the results have provided compelling data to explain and account for the differences between the high speed machining of grey iron and CGI. Ultimately, the results have further motivated efforts for the development of novel high productivity cylinder boring solutions using multiple carbide inserts. The results of this study can be summarized as follows:

1. Changes in graphite shape alone cannot account for the decrease in high speed PCBN tool life between grey iron and CGI. A 50/50 flake/compacted microstructure behaved more similarly to CGI than to grey iron, despite that its mechanical and physical properties were more similar to the grey iron reference. The melt history and metallurgical treatment of the 50/50 flake/compacted alloy was, however, the same as that used for the CGI material. This prompted a more detailed investigation into the influence of the base iron composition and specifically the sulphur content of grey iron and CGI.
2. The high speed PCBN tool life of CGI containing 10% nodularity is 40% longer than for a microstructure containing 50% nodularity and 3.5 times longer than for a microstructure containing 85% nodularity. Limiting the nodularity of CGI as low as possible optimizes tool life.
3. A parallel analysis of a proprietary alloyed grey iron material used for high strength diesel engine cylinder block construction showed that the hardening effect of alloys such as chromium and molybdenum decreases the tool life of PCBN during high speed turning of grey iron by a factor of 10 or more. Again, factors other than graphite shape are clearly active in determining the machinability of cast irons.
4. The presence of manganese sulfide inclusions in grey cast iron leads to the formation of a protective MnS layer on the cutting edge of the inserts. This layer becomes larger and denser as the cutting speed increases causing grey iron tool life to increase with increasing cutting speed. The addition of magnesium during the production of compacted graphite iron results in the formation of relatively hard and abrasive magnesium sulfide (MgS) inclusions rather than soft and pliable MnS inclusions. As a result, no protective layer is formed during CGI machining. This phenomenon accounts for much of the difference observed between the tool life for CGI and grey iron during high speed continuous cutting operations. The inability to increase the sulphur level of CGI or to stabilize MnS inclusions in CGI serves to re-direct the development focus away from metallurgical parameters and toward novel cutting techniques.
5. The critical role of sulphur was validated during high speed turning tests with low-sulphur grey irons. The reduction of the sulphur content of grey irons to typical CGI levels significantly reduces the tool life. When produced at equal sulphur contents (approximately 0.01%S), the difference in tool life during high speed PCBN turning of grey iron and CGI is commensurate with the difference in mechanical properties. As such, the primary difference in tool life can be accounted for by the critical role of MnS inclusions in grey iron and the remaining differences, which are similar to those observed during milling or slow speed carbide turning operations, can be accounted for by differences in mechanical properties.
6. Within the practical range of 70-100% pearlite, lower pearlite levels improve turning operations but impair milling. This opposite behavior for milling and turning makes it difficult to specify an optimal matrix microstructure for the machinability of CGI.
7. An approximate increase of 2.5% pearlite from 97.5% to100% due to manganese, chromium or antimony alloying does not improve PCBN machining.
8. High speed PCBN turning is not affected by pearlite content over the range of 50-100%. The elimination of the 1-5% of free pearlite in typical Cu+Sn stabilized CGI has no effect on PCBN tool life.
9. Antimony alloying of CGI promotes the formation of needle-like graphite spikes on the compacted graphite particles. The addition of antimony does not provide any benefit to the machinability of CGI and simultaneously results in a slight decrease of tensile strength and fatigue strength. Antimony alloying is not recommended for pearlite stabilization in CGI.
10. Small increases in the titanium content from 0.01 to 0.02% reduce CGI tool life by approximately 50%. Further additions render the material effectively unmachinable in both carbide and PCBN continuous cutting operations. Titanium must be kept as low as possible, ideally below 0.01%.
11. The potency of chromium as a pearlite stabilizer is offset by the risk of chill and carbide formation. Chromium must be kept as low as possible, ideally below 0.08%, and should not be used for pearlite stabilization of CGI.
12. A 3.0% silicon-alloyed ferritic CGI provides significant improvements in tool life during carbide turning at 150 and 250 m/min and PCBN turning at 400 m/min, however, this alloy may be too soft (BHN 170) for cylinder block or liner applications. Increasing the silicon to 4.0% increases the hardness into the normal range of grey iron, but simultaneously eliminates much of the machining benefit. While the 3.0% silicon CGI alloy may be suitable for some CGI applications, it is not a viable candidate for cylinder blocks.

In the final analysis, this investigation has shown that the presence of non-metallic inclusions plays a major role in defining the machinability of CGI. In the absence of the soft and pliable MnS inclusions that naturally occur in grey cast irons, particular care must be taken to limit the presence of deleterious elements such as titanium and chromium and preventing chill or segregation carbides. While it is difficult to improve the machinability of CGI, it is very easy to make it worse. All of the known production guidelines for grey and ductile irons regarding carbides, tramp elements and shake-out practice must be equally adhered to for the production of CGI. Perhaps the best way to make the CGI machinable is to make it consistent.

Beyond the efforts to make a controlled and consistent low nodularity CGI, the development of multiple insert boring tools has provided the most significant progress toward solving the requirement for high productivity cylinder boring. Although the cutting speed has been reduced from the conventional grey iron single insert PCBN or ceramic practice of 800 m/min to approximately 100 m/min, the use of six or more carbide inserts in a single cutter has allowed for increased feed rates and longer tool lives. The multiple insert concepts have demonstrated the ability to satisfy productivity and dimensional tolerance requirements during cylinder block machining trials. These technologies, together with consistent CGI microstructures, allow for the successful high volume series production of compacted graphite iron cylinder blocks.

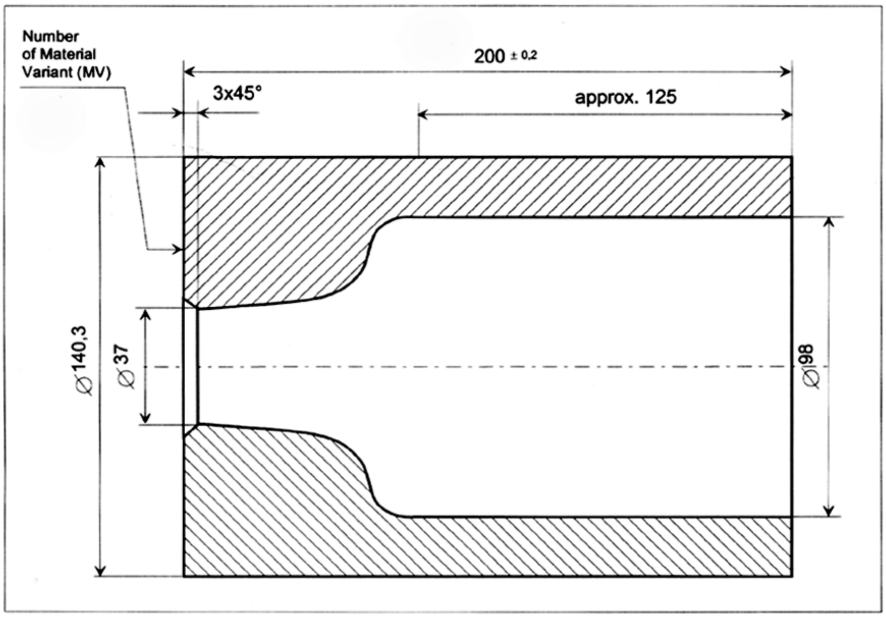
References

1. S. Dawson, I. Hollinger and P. Smiles: The mechanical and physical properties of compacted graphite iron, Global Powertrain Congress, 6-8 October 1998, pp. 85-105.
2. C. E. Bates: Study examines influences on machinability of iron castings, Modern Castings, October 1996, pp. 36-39.
3. R. H. Aborn: What antimony may do for you in grey and ductile iron, AFS Transactions 76-75, pp. 503- 506.
4. H. Weiss: The rotating insert: History, principles, and advantages, Compacted Graphite Iron Design and Machining Workshop, Bad Nauheim, 25-26 November 1998.
5. R. Elliott: Cast Iron Technology, Butterworths, 1988.
6. G. Warnecke, Video: Lehrstuhl für Fertigungstechnik der Universität Kaiserslautern, Institut für den Wissenschaftlichen Film, Göttingen, 1983/1984.
7. H. Shirakawa, S. Mizuno, S. Murai, and K. Naito: Development of high strength cast iron cylinder block assuring high machinability, Journal of Japanese Foundry Engineering Society (in Japanese) Vol. 70, No. 5, 1998, pp.396-401.
8. L. E. Björkegren and K. Hamberg: Ductile iron with better machinability compared to conventional grades, Foundryman, December 1998, pp. 386-391.
9. H. Thordenberg: Helical milling for cylinder bores, Compacted Graphite Iron Machining Workshop 2000, Institute of Production Engineering and Machine Tools, Darmstadt University of Technology, 2 November 2000.

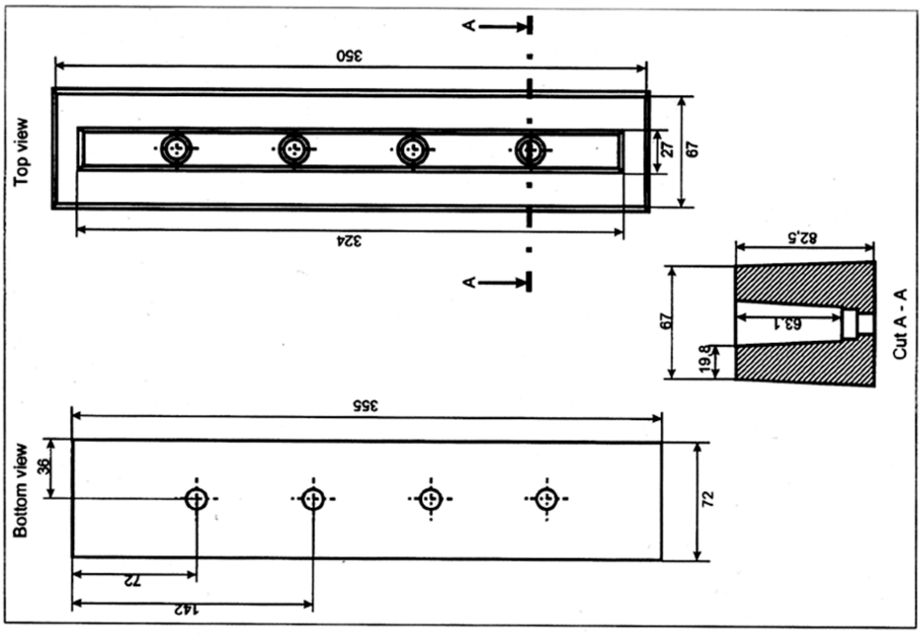
APPENDIX I

Machining Test Pieces

Turning Test Piece



Milling Test Piece



Head Office
SinterCast Ltd
Kingswick House
Kingswick Drive
Sunninghill Berkshire
SL5 7BH
United Kingdom
Tel: +46 150 794 40

Technical Centre
SinterCast AB (publ)
Kungsgatan 2
641 30 Katrineholm
Sweden
Tel: +46 150 794 40

USA
SinterCast Inc
1755 Park Street
Suite 200
Naperville
IL 60563
USA
Tel: +1 630 778 3466

China
SinterCast Trading (Beijing) Co., Ltd
Room 1131, 11/F, Block A, Gateway
No. 18 Xiaguangli
North Road East Third Ring
Chaoyang District, Beijing
China, 100027
Tel: +86 10 5923 1163

Korea
SinterCast Korea Co., Ltd
Rosavallcity No. 310
HyoJa-Ro 194, WanSan-Gu
Jeon Ju City, 560-900
South Korea
Tel: +82 10 9228 1764

SinterCast

— Supermetal CGI —

www.sintercast.com
info@sintercast.com